

Higgs at the Tevatron in Extended Supersymmetric Models

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Supersymmetric models with an additional singlet field offer the Higgs boson the possibility to decay to two pseudoscalars, a . If the mass of these pseudoscalars is above the $b\bar{b}$ threshold, $a \rightarrow b\bar{b}$ is generically the dominant decay mode. The decay $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ may be seen above backgrounds at the Tevatron if the Higgs production cross section is enhanced relative to that of the standard model.

Introduction.—The Higgs boson has successfully resisted discovery as yet. Although precision electroweak data, in combination with the direct top-quark mass measurement at the Tevatron, hint at the existence of a light scalar particle [1], LEP has put a lower bound on the Higgs mass within the standard model (SM), $M_h > 114.4$ GeV [2].

This bound has left some doubt as to whether the minimal supersymmetric standard model (MSSM) is viable. The issue is that this model, which stabilizes the enormous hierarchy between the electroweak and grand-unified or Planck scales, has a fine-tuning problem unless the Higgs boson is somewhat lighter than the current bound.

In addition, the MSSM suffers from the μ -problem. The dimensionful parameter μ is required in order to give mass to the Higgs boson and to communicate the electroweak symmetry breaking between the two Higgs doublets. Hence μ must be at the weak scale, but naïvely we would expect it to be of the order of the grand-unified or Planck scale.

To solve the μ -problem, several extensions have been proposed where the μ -parameter arises after an additional singlet field, which does not interact with the MSSM matter and gauge fields, acquires a vacuum expectation value (vev) [3]. The vevs of the Higgs doublets and the singlet are generically of the same order.

The singlet field provides an additional scalar, a pseudoscalar, and an accompanying Higgsino. These mix with the neutral fields from the two doublets, yielding five neutral Higgs bosons: three scalars and two pseudoscalars. In general, their masses are expected to be comparable; on the other hand, these extended models possess approximate U(1) symmetries, protecting the mass of one pseudoscalar, a . A light pseudoscalar is therefore natural, allowing the decay $h \rightarrow aa$ (where h is approximately SM-like) with a branching ratio of nearly unity [4]. The pseudoscalars then decay to fermion pairs, resulting in a four-fermion final state, to which the LEP searches are less sensitive [5]. If the mass of a is above the $b\bar{b}$ threshold, the dominant final state is $b\bar{b}b\bar{b}$ [6].

In this paper we propose exploring such a scenario at

the Tevatron. The Higgs boson is dominantly produced singly and subsequently decays via $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$. We calculate the backgrounds to this signal using the multi-purpose code MadEvent [7]. It is usually assumed, either explicitly or tacitly, that this background overwhelms the signal, and we confirm that this is the case. However, we find that if the signal is sufficiently enhanced, then it emerges from the background. This opens the question of whether there exists models with enhanced Higgs production and with a significant branching ratio for the above decay mode.

We do not restrict our study to one particular model beyond the MSSM but consider the general case, where M_h varies between 110 and 150 GeV. This approach is motivated by the fact that these extended models include a large region in parameter space with M_h in this range and with M_a between zero and 200 GeV [8].

In this mass region, the SM Higgs production cross section at the Tevatron is less than 1 pb, via $gg \rightarrow h$; however, in the MSSM the cross section is much larger for large $\tan\beta$, with both $gg \rightarrow h$ and $b\bar{b} \rightarrow h$ contributing [9]. It is an open question whether there exist extensions of the MSSM which maintain this large production rate, while at the same time yielding a significant branching ratio for $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$.

Background.—Let us consider the general case of a scalar particle, h , which almost exclusively decays to two lighter pseudoscalars (or scalars), a , followed by the decay to b quarks.

The dominant background is due to QCD multijet production, with varying combinations of true b tags and mistagged jets. As we will see, we must require at least three b tags to have a reasonable signal-to-background ratio, so we have to consider the backgrounds ($j = u, d, s, c, g$)

- $p\bar{p} \rightarrow b\bar{b}b\bar{b}$;
- $p\bar{p} \rightarrow b\bar{b}bj$;
- $p\bar{p} \rightarrow b\bar{b}jj$, where one jet is mistagged;
- $p\bar{p} \rightarrow bjjj$, where two jets are mistagged;
- $p\bar{p} \rightarrow jjjj$, where three jets are mistagged.

TABLE I: Parameters and cuts.

Parameters	
renormalization scale	$\langle p_T \rangle$
factorization scale	$\langle p_T \rangle$
PDF	CTEQ6L
b mass	$m_b = 0$
Cuts	
rapidity	$ \eta < 2.0$
separation	$\Delta R > 0.4$
jet 1	$p_T > 20$ GeV
jets 2–4	$p_T > 15$ GeV
invariant mass of two jets	$m_{jj} > 10$ GeV
Tagging efficiencies	
b tag	50%
mistag of c	10%
mistag of light quark or gluon	1%

The CDF and D0 collaborations have performed searches for neutral Higgs bosons produced in association with bottom quarks, followed by $h \rightarrow b\bar{b}$, using a secondary-vertex trigger [10]. Guided by their analyses, we chose the cuts listed in Table I. The requirement on the minimum invariant mass of any two jets may not be necessary, but it eliminates many background events and therefore makes the event generation more efficient.

The different background processes sum to an enormous background of 380 nb prior to b tagging. In order to extract the signal, we must require that three or more jets are tagged. In reality, the tagging efficiency is a p_T and η dependent function. For simplicity, and to allow others to easily reproduce our results, we approximate the tagging efficiency and the mistag rates by the constant values listed in Table I. This overestimates the actual capabilities of the detectors, but is sufficient for a crude analysis.

Tagging three or more jets, the background drops dramatically to 63 pb. Table II lists the cross sections of the various processes, categorized by the number of b and c jets present. We see that $b\bar{b}jj$ with one mistagged light jet makes up about half of the background, followed by $b\bar{b}bj$ and $b\bar{b}bb$. The largest backgrounds with mistagged c jets are $b\bar{b}cj$ and $b\bar{b}c\bar{c}$, but they are relatively small.

Let us now consider different windows in the (M_h, M_a) -plane, where we choose the masses of h and a to be $M_h = 110, 130, 150$ GeV and $M_a = 20, 40, 60$ GeV. The jets are paired such that their invariant masses are as close as possible. The windows have a size of 30 GeV for the invariant $b\bar{b}$ and $b\bar{b}b\bar{b}$ masses, again guided by Ref. [10]. The results are shown in Table III; the background is between 10 and 15 pb for all masses considered.

Signal.—The signal events have to pass the same cuts as the background processes (see Table I). Table IV shows the product of the acceptance and tagging efficiency for

TABLE II: The cross sections (pb) of the various background processes $p\bar{p} \rightarrow jjjj$ after the cuts and tagging efficiencies of Table I. The cross sections are organized by the number of b and c jets in the event.

	total	$n_c = 0$	$n_c = 1$	$n_c = 2$	$n_c = 3$	$n_c = 4$
total	63	54	4	5	0.2	0.1
$n_b = 0$	3	0.8	0.2	1	0.2	0.1
$n_b = 1$	1	0.5	0.05	0.5	0	
$n_b = 2$	40	33	4	3		
$n_b = 3$	10	10	0.1			
$n_b = 4$	9	9				

TABLE III: Background cross sections (pb) for different choices of M_h and M_a with window sizes of 30 GeV.

	$M_a = 20$ GeV	$M_a = 40$ GeV	$M_a = 60$ GeV
$M_h = 110$ GeV	15	14	12
$M_h = 130$ GeV	15	15	13
$M_h = 150$ GeV	11	11	11

the different choices of M_h and M_a .

For a discovery of h , the ratio S/\sqrt{B} , where S and B are the signal and background, must be at least five. We use 2 fb^{-1} of integrated luminosity to derive the minimum signal cross section for a discovery of h . We assume that all signal events pass the mass reconstruction constraints, which is a good approximation. We use an ideal branching ratio for $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ of 100%; the minimum signal cross section is increased by a factor of $1/BR$ for other branching ratios. The results are given in Table V.

If one tags all four jets, the tagging efficiency for the signal drops by a factor of 5, due in part to combinatorics. Looking at Table II, one finds that the only significant background with all four jets tagged is $b\bar{b}b\bar{b}$, and this also drops by the same factor of 5. Since this background is $1/7$ of the total background with three or more tags, the overall gain in signal significance with four tags is a modest factor of $\sqrt{7/5} \approx 1.2$.

Discussion.—The minimum cross section required for discovery is an order of magnitude greater than the SM Higgs production cross section, confirming the belief that the backgrounds overwhelm the signal in this case. In-

TABLE IV: Acceptance \times tagging efficiency of the signal for different choices of M_h and M_a .

	$M_a = 20$ GeV	$M_a = 40$ GeV	$M_a = 60$ GeV
$M_h = 110$ GeV	0.04	0.04	—
$M_h = 130$ GeV	0.06	0.05	0.14
$M_h = 150$ GeV	0.09	0.08	0.12

TABLE V: Discovery cross section for the signal (pb) with 2 fb^{-1} of data if all signal events pass the mass reconstruction constraints, assuming a branching ratio for $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$ of 100%.

	$M_a = 20 \text{ GeV}$	$M_a = 40 \text{ GeV}$	$M_a = 60 \text{ GeV}$
$M_h = 110 \text{ GeV}$	12	11	—
$M_h = 130 \text{ GeV}$	7	9	3
$M_h = 150 \text{ GeV}$	4	5	3

creasing the integrated luminosity to 8 fb^{-1} decreases the minimum cross section by a factor of two, still not enough to discover a SM-like Higgs in this decay mode. However, if there exist models in which the Higgs production cross section is enhanced by an order of magnitude, while still maintaining a significant branching ratio for $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$, then it appears possible to discover such a Higgs at the Tevatron. This is an open question in extensions of the MSSM.

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[1] ALEPH, DELPHI, L3, OPAL and SLD Collaborations, LEP Electroweak Working Group, SLD Electroweak and

Heavy Flavour Groups, Phys. Rept. **427**, 257 (2006).
[2] R. Barate *et al.* [LEP Working Group for Higgs boson searches], Phys. Lett. B **565**, 61 (2003).
[3] For a recent review, see E. Accomando *et al.*, arXiv:hep-ph/0608079.
[4] J. F. Gunion, H. E. Haber and T. Moroi, arXiv:hep-ph/9610337; B. A. Dobrescu, G. Landsberg and K. T. Matchev, Phys. Rev. D **63**, 075003 (2001); B. A. Dobrescu and K. T. Matchev, JHEP **0009**, 031 (2000); U. Ellwanger, J. F. Gunion and C. Hugonie, arXiv:hep-ph/0111179; JHEP **0507**, 041 (2005); U. Ellwanger, J. F. Gunion, C. Hugonie and S. Moretti, arXiv:hep-ph/0305109; arXiv:hep-ph/0401228; R. Dermisek and J. F. Gunion, Phys. Rev. Lett. **95**, 041801 (2005); Phys. Rev. D **73**, 111701 (2006); arXiv:hep-ph/0611142; S. Chang, P. J. Fox and N. Weiner, JHEP **0608**, 068 (2006); arXiv:hep-ph/0608310; P. W. Graham, A. Pierce and J. G. Wacker, arXiv:hep-ph/0605162.
[5] S. Schael *et al.* [ALEPH, DELPHI, L3 and OPAL Collaborations and LEP Working Group for Higgs Boson Searches], Eur. Phys. J. C **47**, 547 (2006).
[6] Scenarios where other decay channels become dominant have been studied in Refs. [4] as well.
[7] T. Stelzer and W. F. Long, Comput. Phys. Commun. **81**, 357 (1994); F. Maltoni and T. Stelzer, JHEP **0302**, 027 (2003).
[8] V. Barger, P. Langacker, H. S. Lee and G. Shaughnessy, Phys. Rev. D **73**, 115010 (2006).
[9] For examples, see T. Hahn, S. Heinemeyer, F. Maltoni, G. Weiglein and S. Willenbrock, arXiv:hep-ph/0607308.
[10] A. A. Affolder *et al.* [CDF Collaboration], Phys. Rev. Lett. **86**, 4472 (2001). V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **95**, 151801 (2005);